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Review on structural damage assessment via transmissibility with vibration based measurements

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Abstract. In this study, transmissibility based damage assessment techniques with vibration measurement are reviewed with highlighting the recent advancements since damage might induce severe changes and cause huge economic losses in both civil and mechanical engineering structures. In recent years, transmissibility underwent booming and divergent application for damage assessment both in experimental model and engineering application, and this review provides a fundamental understanding for transmissibility based damage assessment by summarizing those research outputs, which can serve as useful reference for further investigations.

1. Introduction

Damage assessment, as the main issue in structural health monitoring (SHM), underwent more than centuries since maintenance and repairing were indispensable after the long-term serviceability of almost all constructed structures such as buildings and bridges. However, from the wide use of civil infrastructures like oil pipeline, long span bridge, tall buildings and so on, and mechanical structures like rotational machines, damage assessment has become increasingly essential as the failure of such large scale or highly integrated structures may lead to huge economic loss. During last decades, damage assessment underwent booming development, thus, leading to abundant research outputs with applications in engineering including in time and frequency domain techniques, empirical and model-based approaches. Critical reviews on vibration based damage identification can be found in [1, 2], where vibration based damage identification techniques were summarized in a thorough perspective [1], while the review focused on identifying damages in composite structures with vibration testing [2].

For SHM/damage assessment, damage is the key and fundamental conception that should be clearly defined, which includes deterioration and degradation, and so on. A widely accepted general definition is given by Sohn et al. [1] as "*changes introduced into a system that adversely affect its current or future performance. Implicit in this definition is the concept that damage is not meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial, and often undamaged, state*." In [2], the authors summarized the different damage types like stiffness change, boundary condition change, mass change or connectivity change. Then the key idea for damage identification would be seeking the difference between undamaged pattern and damaged pattern often via some structural characteristics like mechanical, electrical, or magnetic properties, and thus predicting the occurrence of possible damage. From this perspective, those newly developed techniques like eddy current, ultrasonic testing, and X ray, are applied.

1.1. Schemes of damage identification

In SHM, damage identification/assessment is the key issue [3-10]. And for damage identification, the damage state of a system can be described as a five-step process along the lines of the process discussed in [11]. The damage state is described by answering the following questions [1, 11]: (1) Is there damage in the system (existence)? (2) Where is the damage in the system (location)? (3) What kind of damage is present (type)? (4) How severe is the damage (extent)? (5) How much useful life remains (prognosis)?

In [3], the authors summarized damage identification methods into two categories, namely physical model based, and statistical/data model based, where physical model based approaches aim to detect defects/deteriorations via the difference between real structural response and its numerical prediction, where finite element (FE) model requires well understanding of the physical model as prior. As finite element analysis (FEA) should be well conducted, it may require experience and skills. Finite element analysis has been widely used in the literature for many engineering applications that have been recently published [12-30] . The woSystem identification can also applied to extract the structural dynamic characteristics. FE model updating is extended to damage identification while initially designed for optimize the FE model. As one can see, the demanding of physical model immediately sets an overwhelming conundrum and largely restricts its potential application, since in actual engineering the obtaining of exact physical model constantly encounters suffering from boundary conditions, loads, environmental parameters and so on. In addition, the FE model for large-scale structures will require high cost in computation, which also implies the necessity in seeking cost-effective approaches for damage assessment. In such approaches, techniques involve ARMA family models in time domain, dynamic stiffness, and algorithms like Radial Basis Function (RBF), BAT algorithm [6]. Note that damage not only means the damage in reinforced concrete structures, bridges, composite beams, but also damage in fatigue-induced damage.

On the other hand, statistical/data model based methods try to unveil the damages according to the response analysis utilizing pattern recognition, machine learning and so on, which will avoid the measurement of structural excitations, and thus simplifying the damage identification procedure. In [1], the authors described damage assessment problem as one of statistical pattern recognition paradigm, which consists of a four-part process: (1) Operational Evaluation; (2) Data Acquisition, Fusion, and Cleansing; (3) Feature Extraction and Information Condensation; (4) Statistical Mode Development for Feature Discrimination. Note that the key step is to extract a proper feature to interpret the corresponding damage. One feature might be function of only one kind, or also function of several kinds of damage. Features like modal frequencies, damping, and so on are commonly used in the previous investigation for SHM. Pattern recognition methodologies are then adopted to better discriminate the damaged patterns from the undamaged ones. Machine learning algorithms, discriminant analysis, pattern recognition and so on have been introduced into damage identification for facilitating SHM analysis particularly in large-scale or complex structures.

1.2. Significance of this study

This study tries to illustrate the main developments of damage assessment techniques via the adoption of transmissibility in the past years, and thus to give a valuable reference for further investigation. Conventional techniques may require the excitation to be white noise, or demand the measurement of excitation, while the use of transmissibility solved these problems. And booming and diverge developments might be better to be summarized for several categories in order to give a clear and efficient understanding.

2. Damage assessment via transmissibility

For vibration based damage assessment techniques, modal testing is the commonest tool, which might be divided into Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA). The key difference is that EMA normally takes the testing object into laboratory and apply excitation, and then conduct modal analysis, while OMA directly measures the dynamic response during operating condition of the tested object, and tries to unveil the structural characteristics from the measured data. The advantage of OMA in comparison with EMA is that there is no restriction to the testing object. This gives the possibility in applying the technique to large scale structures like wind blades and suspension bridges. Another merit of OMA is that no necessity is required for the excitation. And transmissibility based technique is a typical one based on OMA.

Transmissibility, a conception raised decades ago, has been applied in damage assessment during the past years. Some general reviews can be found in [31-33] and a detailed review is given in [34]. Transmissibility definition is thoroughly reviewed and discussed in [31], and application of transmissibility in force identification is illustrated in [32]. The application of transmissibility in damage assessment is generally reviewed in [3, 33], while a more general review of transmissibility referring to theoretical development and engineering application is given in [34]. Conventional damage assessment techniques via transmissibility can be found in [35-40], while from 2010, transmissibility has been increasingly widely applied in damage assessment and will be illustrated hereinafter.

2.1. Transmissibility definition.

A general definition for transmissibility is the ratio between two structural dynamic responses, which can be indicated as:

$$T_{(i,j)} = \frac{X_i}{X_j} \tag{1}$$

where i, j means the nodes of two outputs, and X_i, X_j mean the frequency spectrum of dynamic response x_i, and x_j. Note transmissibility is also extended into nonlinear part holding the same philosophy [41].

Similar to coherence in modal analysis, transmissibility coherence (TC) [34, 42] is defined as:

$$TC_{(i,j)} = \left| \frac{G_{ij}^2}{G_{ii}G_{jj}} \right| \tag{2}$$

where G means the cross- or auto- spectrum.

2.2. Damage assessment with transmissibility.

To all transmissibility-based techniques, the net change can be the easiest one in identifying damage [36], and later transmissibility is extended with curvature by analog with FRF curvature [43]. The net transmissibility change is considered in percentage with respect to the undamaged baseline with accumulating in a specific frequency range [33]. Outlier analysis is also introduced in [44]. Neural networks are another alternative, which try to predict damage after being trained by taking transmissibility as a feature [38]. Autoregressive model is also introduced and control chart and factor analysis is delivered [45]. Euclidean distance and cosine similarity measure are introduced to detect the damages in steel platforms [46]. A detection methodology combining transmissibility with Mahalanobis distance and principal component analysis (PCA) are applied in damage localization in real aircraft wing [47].

Unlike pattern recognition algorithms, an indicator might be easier and simpler in adoption. From this idea, modal assurance criterion (MAC) is introduced for damage detection and damage localization and damage quantification [48]. This idea also extends to a specific frequency range of transmissibility since some parts might be contaminated by noise [49]. Since the key idea of MAC is to estimate the similarity between two vectors, it can also be applied to transmissibility extended vectors, like inverse subtraction transmissibility function [50], transmissibility coherence [3, 34, 42, 51]. For instance, in [2, 42], the authors considered that the peaks of transmissibility subtraction were in consistence with the poles of structures, vectors were constructed around the peaks with all transmissibilities of the structural system, and later MAC was applied to identify the damages. Similar idea is extended to transmissibility coherence [51, 52].

For damage assessment, since the key idea is to unveil the difference between undamaged and damaged conditions, distance measure is the commonest way to be considered [8, 53]. Mahalanobis distance and Euclidean distance are compared for transmissibility and FRF, with drawing out that Mahalanobis distance has more noise tolerance than Euclidean distance [54]. Cosine distance is adopted after condensing the transmissibility with PCA, with comparing with distance measure [55]. In they compared city block distance, Chebyshev distance, Minkowski distance, Mahalanobis distance with taking PCA in condensing the transmissibility. Transmissibility based damage assessment has also considered in nonlinear part [56], metro tunnel structure [57], bridges [58], and so on. Certainly other transform like wavelet transform is also discussed [59].

3. Conclusions

This study illustrated the development of transmissibility based damage assessment techniques and also generally discussed the conventional vibration based damage assessment techniques, which may give a valuable reference for further investigation. Conventional techniques may require the excitation to be white noise, or demand the measurement of excitation, while the use of transmissibility solved these problems. And booming and diverge developments were summarized for several categories in order to give a clear and efficient understanding.

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